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Black-Hole TeV Plerion in the Galactic Center

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(Astrophys. J. 617, L123, 2004)

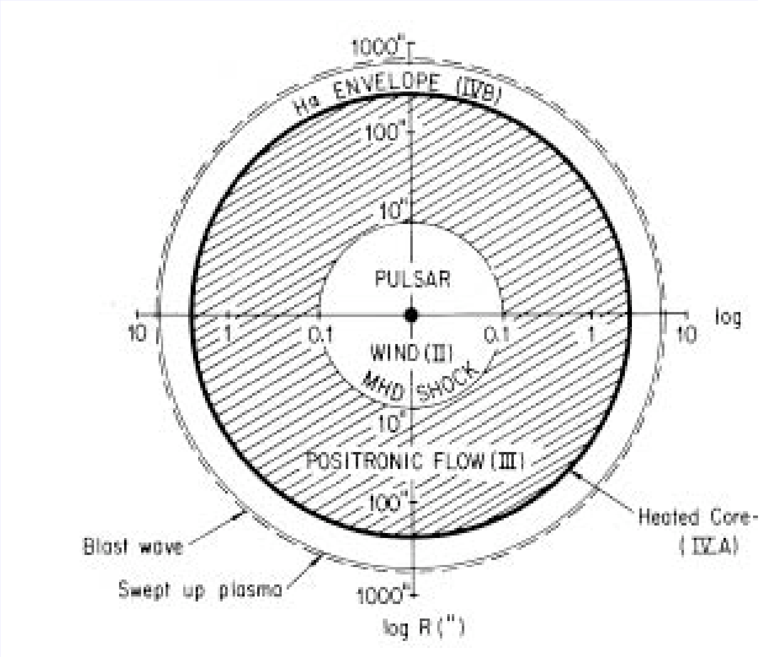
Crab nebula

Plerions: *SN remnans powered by neutron stars*

Very efficient Galactic accelerators of electrons;
bright sources of non-thermal radiation;
energy supply through relativistic wind.

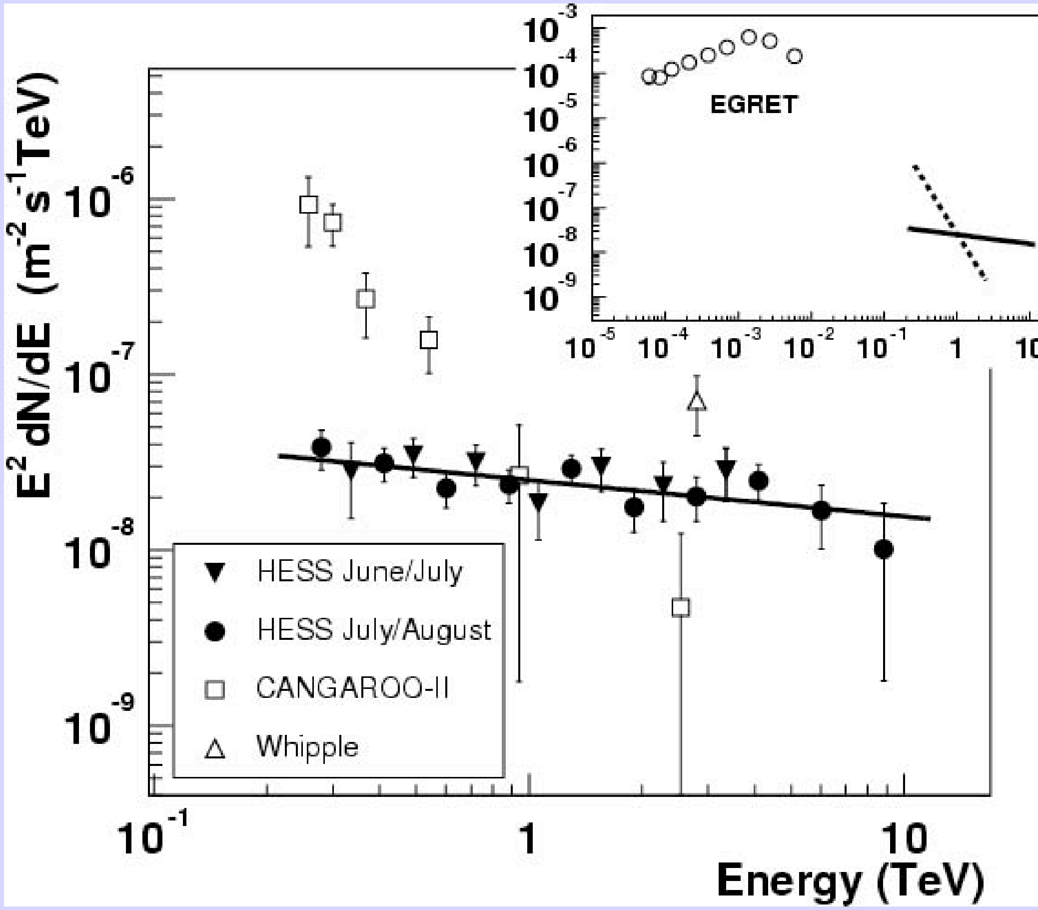
Crab Nebula – prototype plerion, and
(the most) prominent non-thermal source
from radio to TeV gamma-rays , L_{rad}~10^{38} *erg/s*

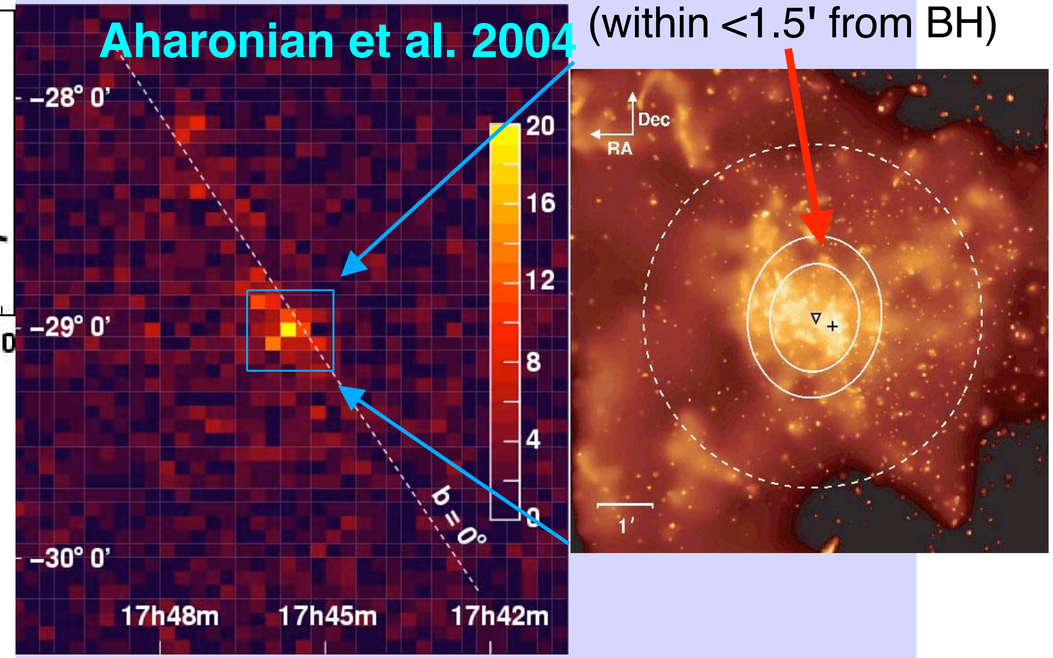
Crab Nebula



(Kennel & Coroniti 1984)

TeV Emission from the Galactic Center





Characteristics of TeV emission:

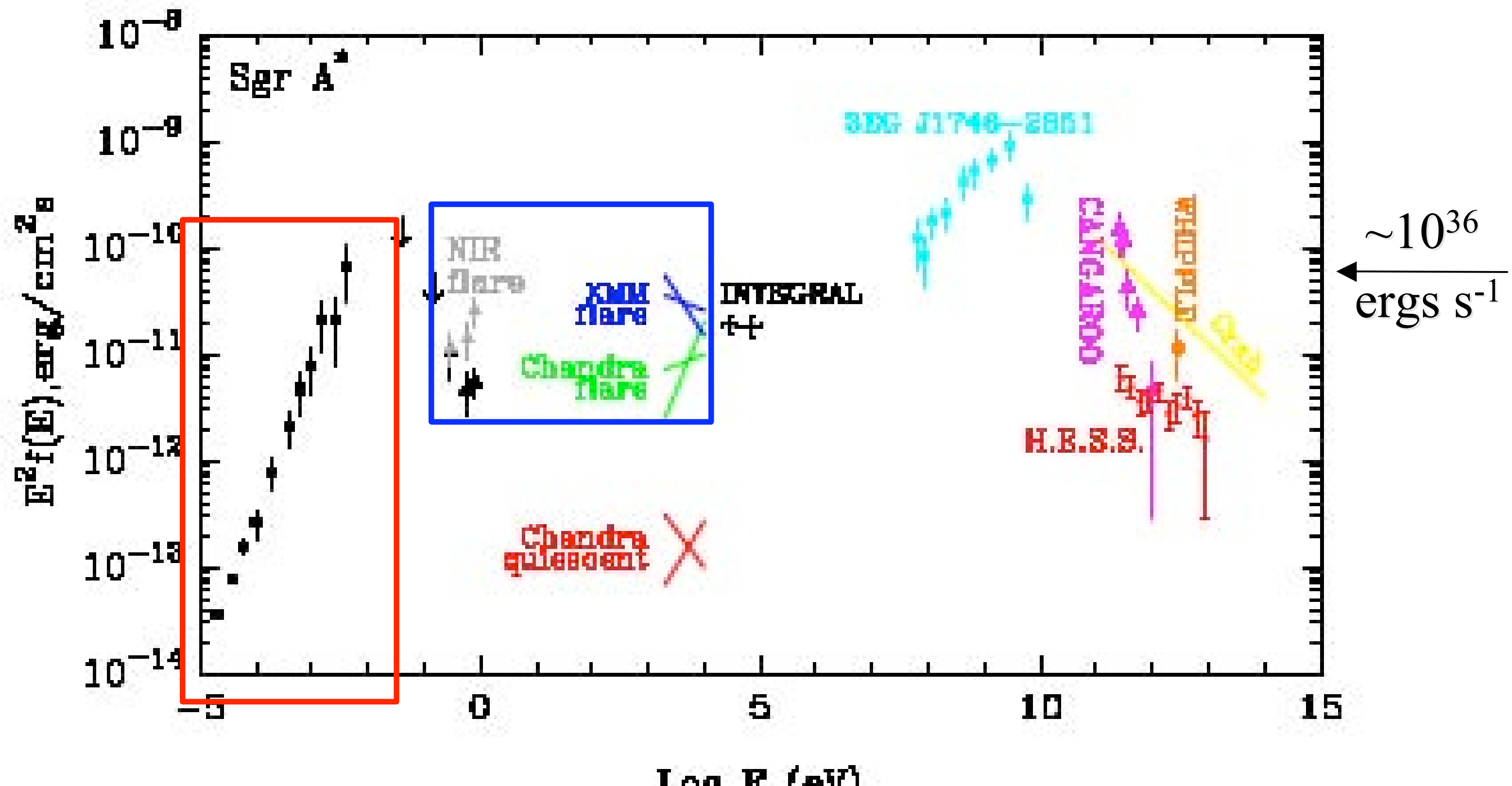
hard power-law spectrum,

$\alpha \approx$ 2.1-2.3

no variation of TeV flux detected;

total L_{TeV}*~*10^{35} *erg/s*

Multiwavelength Observations of Sgr A*



(Aharonian and Neronov 2004)

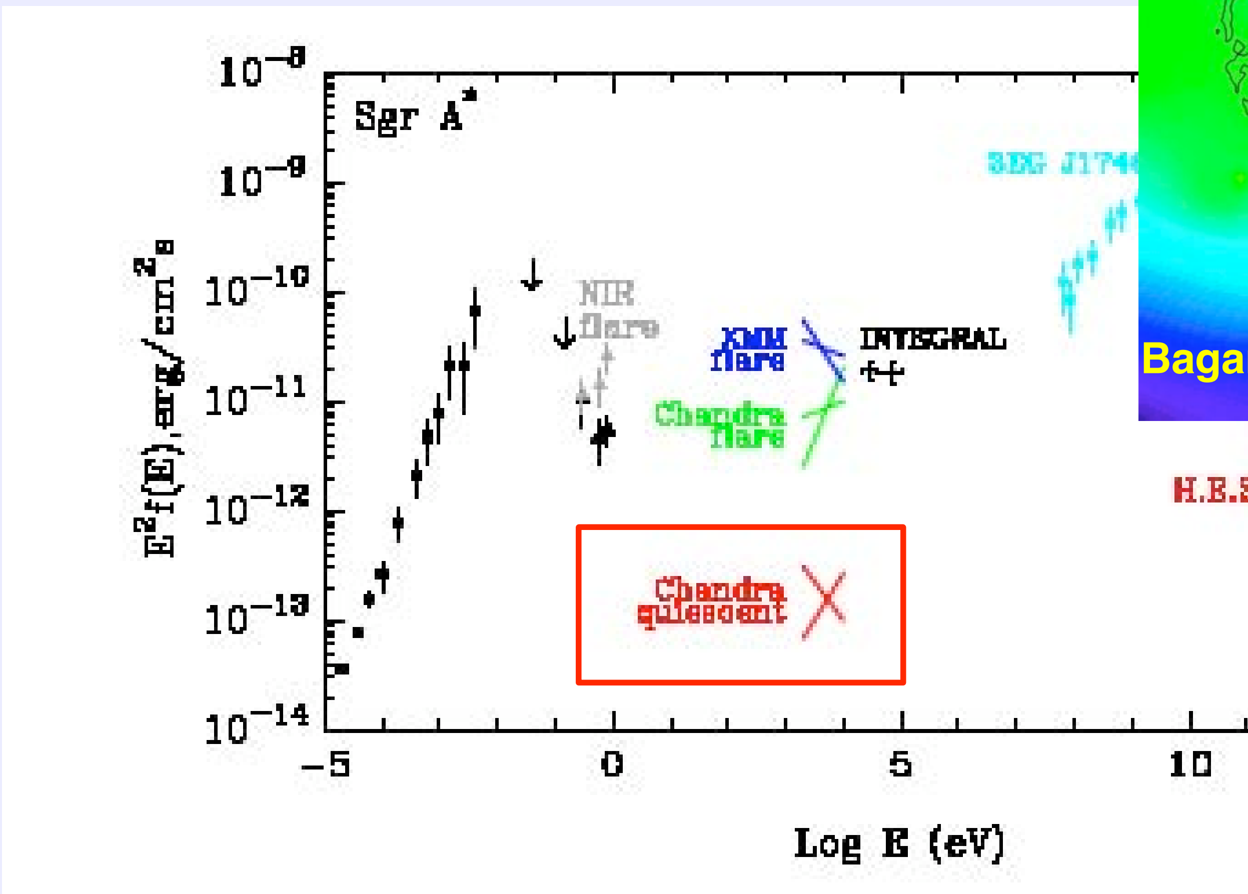
Radio: hard spectra with $S_\nu \propto \nu^{0.3}$, cutoff above 10^{12} Hz; total $L_{radio} \sim 10^{36}$ erg/s
size ~0.2 mas ($R_{rad} \sim 20\ R_{Sh}$) at ~100 GHz (Krichbaum et al. 1998)

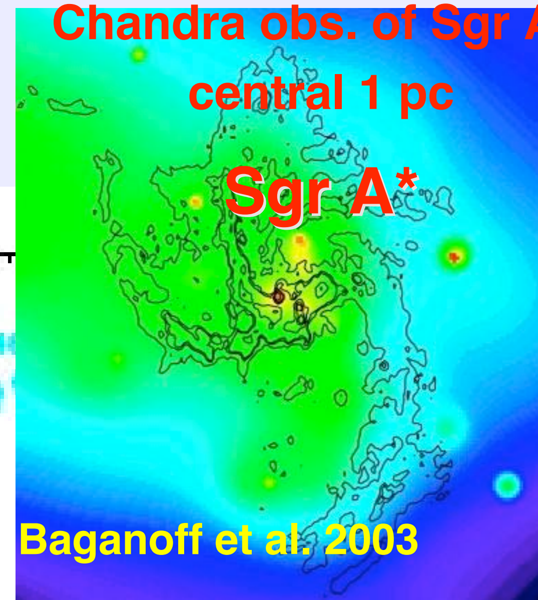
Near-IR: flares (*factor* ~ 2) on timescale **Δt** ~20 min , $R_{NIR} \leq c\ \Delta t \approx 30\ R_{Sh}$

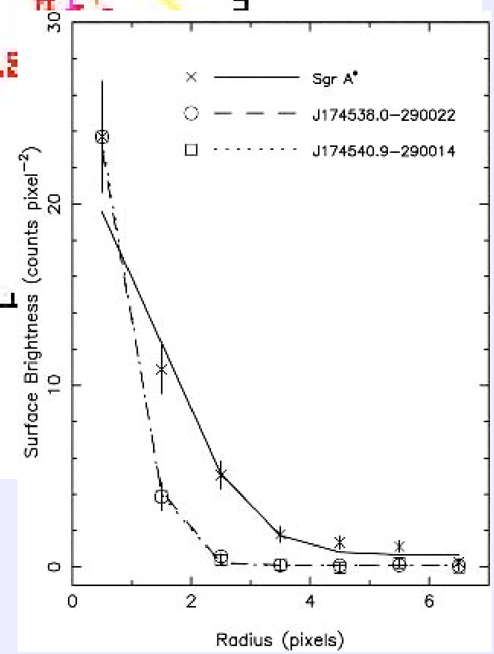
X-ray *flares* : (*factor up to* 2 *orders*; ~ 1 *per day*), observed Δt ~ 200 s =>

$R_X \leq c\ \Delta t = 5\ R_{Sh}$ (!)

X-ray Observations of Sgr A*: *quiescent*







Luminosity: L(2-10 keV) = $2.4 \cdot 10^{33}$ erg/s
spectral index: α=2.-3. ($f_E \propto E^{-\alpha}$)
(Baganoff et al. 2003)

Extended (!):
r~0.7" ~10^{17}cm

Production of TeV radiation: *possibilities & problems*

- Compton (*Inverse*): electron scattering on 'target' photons
  convenient photon field - radio/FIR,
  radiation intensity $\propto u_{rad-}\gamma^2$, - effective mechanism
  however, parallel process for the same electrons
- Synchrotron: radiation in the magnetic field
  intensity $\propto u_{B-}\gamma^2$
  typical photon energy by TeV electrons – X-ray domain
  $F(TeV) / F(keV) = u_{rad}/u_B$; *observed ratio ~40*
- TeV production close to BH *problematic*
  (a) magnetic field B~0.1 G << B_{eq}~10 G
  would be dynamically unimportant for the accretion (??)
  (b) TeV must vary with X-ray flares (!)

Alternatives: *hadron origin*

- Proton-proton interactions:

$$p+p \rightarrow \pi^0\ (+\ X) \rightarrow 2\gamma$$

(a) for $n \sim 10^8\ cm^{-3}$ close to BH

protons with $L_{accel} \sim 10^{40}$ erg/s are needed (??)

(b) production of *e* about the same as γ

$\Rightarrow$ same problems as with Compton origin remain:

- Photomeson interactions:

$$p + (photon) \rightarrow \pi^0\ (+\ p) \rightarrow 2\ \gamma$$

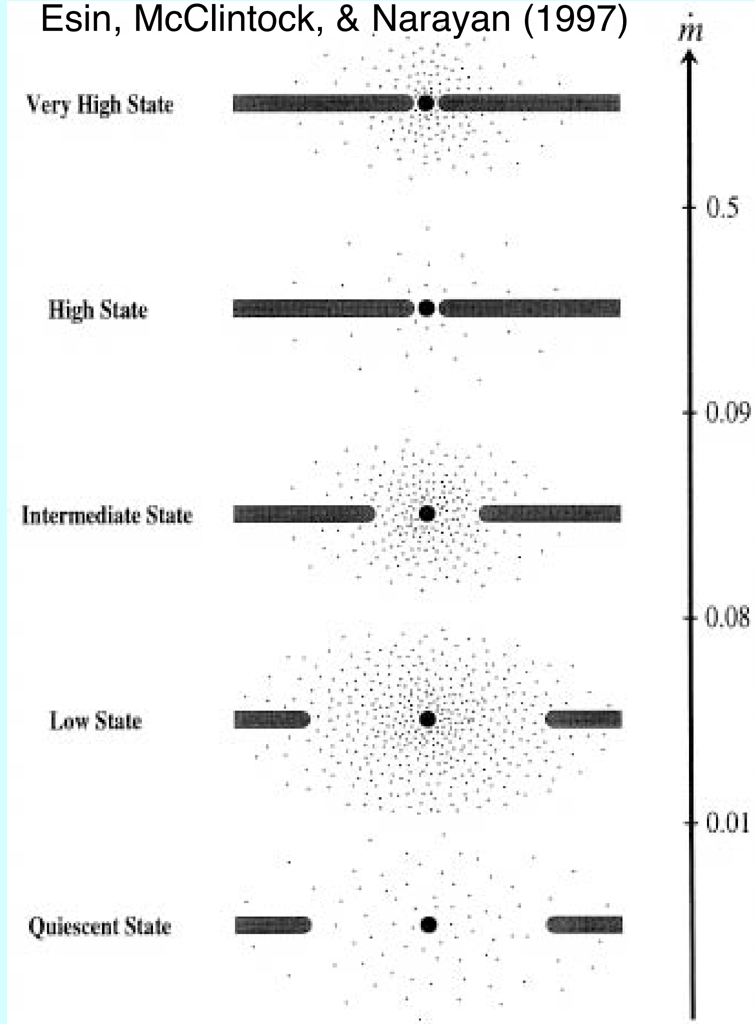
(a) *however*, electrons are produced as well:

$$p + (photon) \rightarrow \pi^+\ (+\ n) \rightarrow e^+$$

(b) energetics needed is higher than for $p+p$

Accretion Physics in the ADAF/ADIOS Regime

Esin, McClintock, & Narayan (1997)



Advection-dominated accretion flow (ADAF) model for compact objects accreting at low Eddington accretion rate

$$\dot{m} \equiv \eta_{BH} \dot{M} c^2 / L_{Edd}$$

Radiant luminosity at the level

$$L_{rad} = \dot{m} L_{Edd} (\dot{m} / \dot{m}_*) ,$$

$$\dot{m}_* \approx 0.1$$

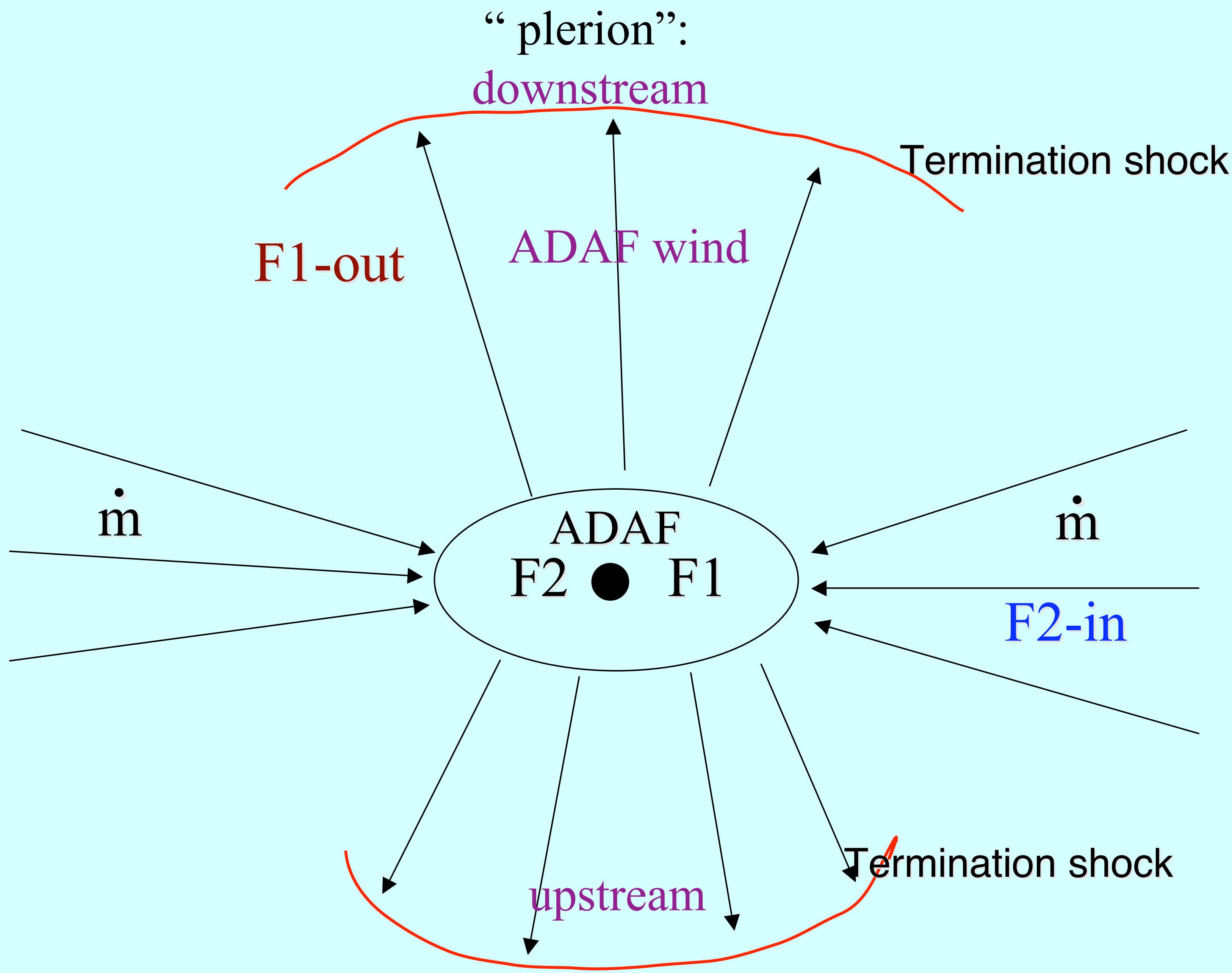
is fraction of accretion power that is advected into black hole or convectively escapes

$$L_{th} = L_{rad} = 10^{36}\, ergs\, s^{-1} \Rightarrow$$

$$\dot{m}_{GCBH} \approx 1.5 \times 10^{-5}$$

But more likely are accretion rates $\leq 10^{-6}$ (*non-thermal radio*)

Plerion powered by wind from GC Black-Hole



$R_{shock} \leq R_X \sim 8*10^{16}$ cm

The Black Hole Plerion

Particle escape by convective outflow in advection-dominated inflow-outflow source (ADIOS) extension (Blandford & Begelman 1999) of ADAF model.

Assume a wind power

$$L_{wind} = 10^{37} L_{37}\, ergs\, s^{-1}$$

With speed $v_{wind} \approx c/2$ directed into solid angle $\Omega \approx 1$ sr

Wind terminates at a subrelativistic shock at

found by equating thermal gas pressure with energy density of the wind

Electrons and protons accelerated at the shock (first-order Fermi acceleration).

Electrons emit X-ray synchrotron radiation to form quiescent X-ray emission

and Compton scatter

- ADAF emission
- 10^{13} Hz emission from cold dust ring around Sgr A*

Crab Nebula: X-rays

Parameters of the plerion:

Post-shock region *at* $R \leq 10^{17}$ cm

- Magnetic field:

  B~0.1 mG – *from the TeV/X-ray flux ratio*

  could increase at larger distances downstream (*compression*)

- Mean plasma speed:

  v ~ 500-1000 km/s – *from the requirement that* $R_X \sim 10^{17}$ cm

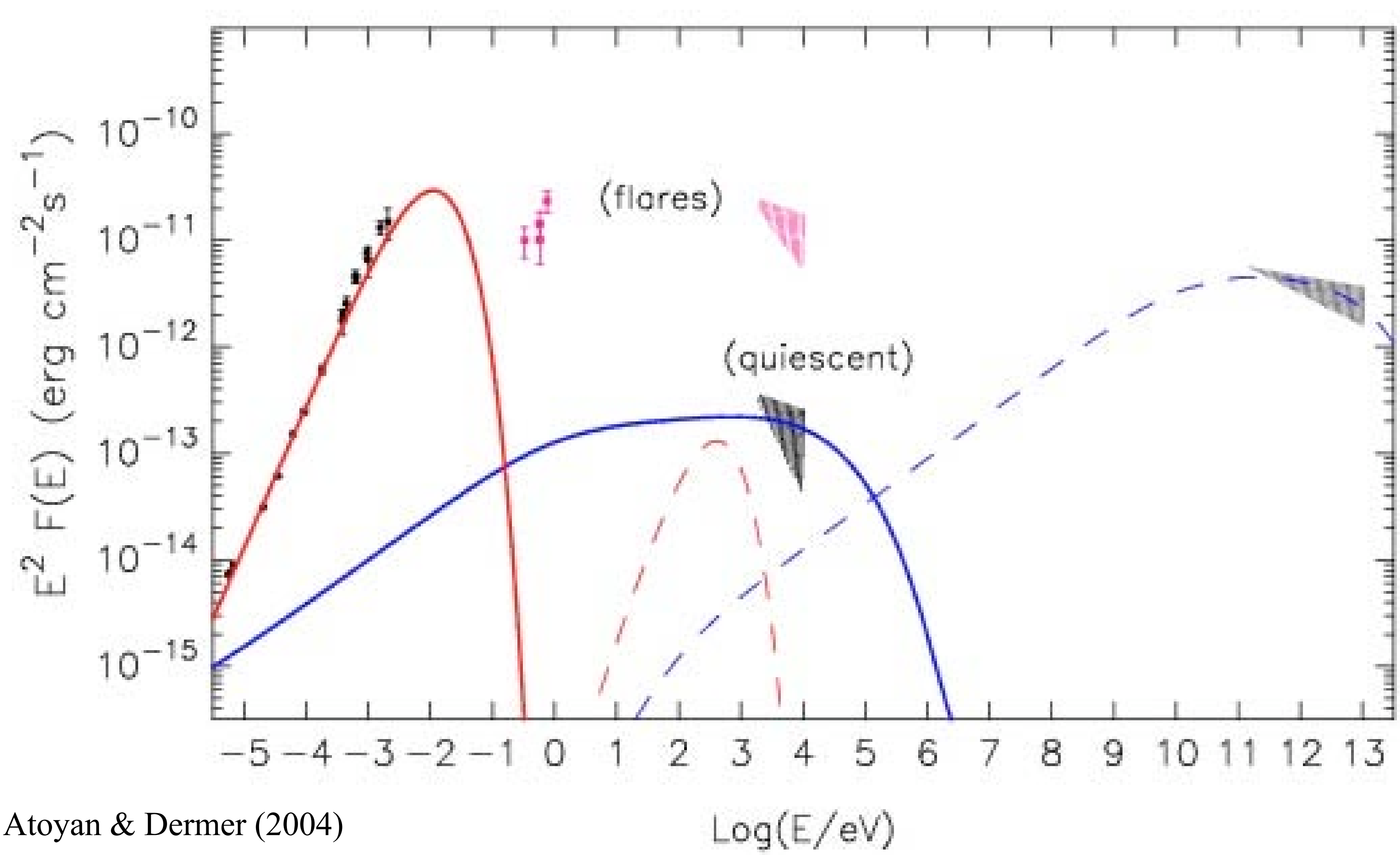
  (X-ray emitting electrons should have time to cool)

- Total power of the outflow:

  $L \sim 10^{37}$ erg/s - *to explain the TeV flux,*

  can be up to 10^{38} erg/s

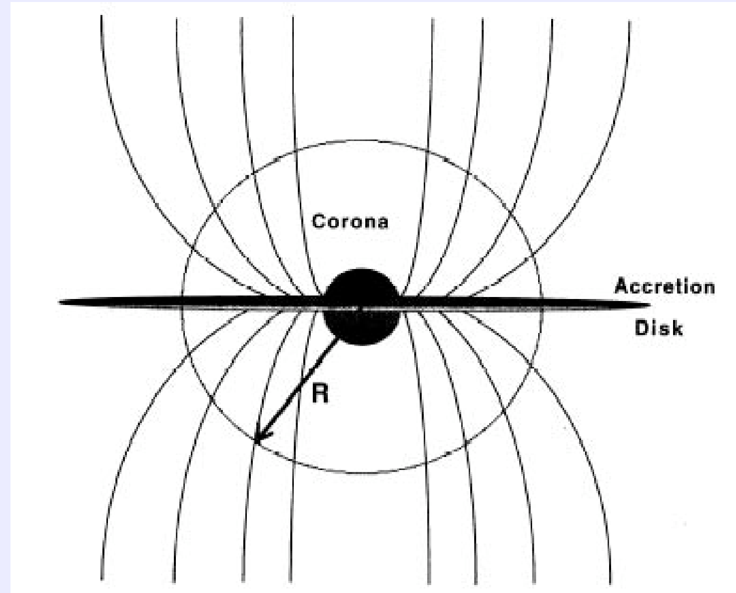
Quiescent X-ray, TeV, + radio/sub-mm



Atoyan & Dermer (2004)

Other pieces of the puzzle: *radio flux*

Acceleration of electrons in the ADAF



Second-order Fermi accelerated electrons on plasma turbulence (Liu, Petrosian, Melia, 2004):

$$\frac{B^2}{8\pi} = \varepsilon_B \left(\frac{\eta_{BH} \dot{M} c^2}{4\pi R^2 c}\right) \Rightarrow B(G) \approx 30 \varepsilon_B^{1/2} L_{36}$$

for a region of size 20 r_{Sh}

Equating acceleration rate of electrons by Whistler turbulence to synchrotron loss rate:

$$\gamma_0 \approx 200 (\varsigma_{-1} \varepsilon_{B,-1})^{1/3} L_{36}^{1/2} \left(\frac{\tau_T}{2 \times 10^{-4}}\right)^{-11/18}$$

(Dermer, Miller & Li 1996; Liu, et al 2004)

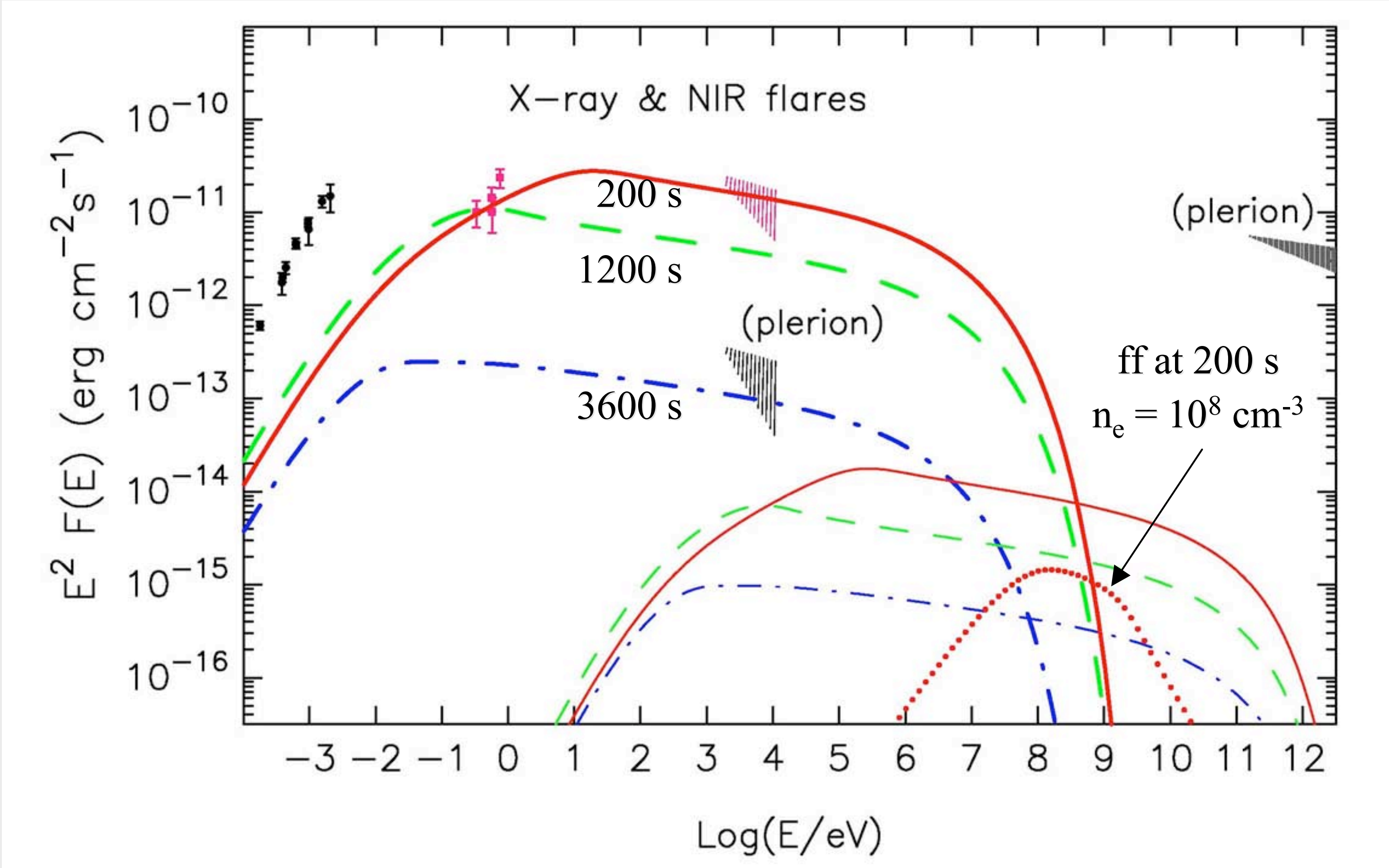
Steady-state electron spectrum:

$$N(\gamma) \propto \gamma^2 \exp(-\gamma / \gamma_0)$$

– Production of radio flux by relativistic electrons with Maxwellian ('monoenergetic') distribution:

$$S_\nu \propto \nu^{0.3} \exp(-\nu / \nu_0)$$

Flaring X-ray & NIR emissions from ADAF/BH region



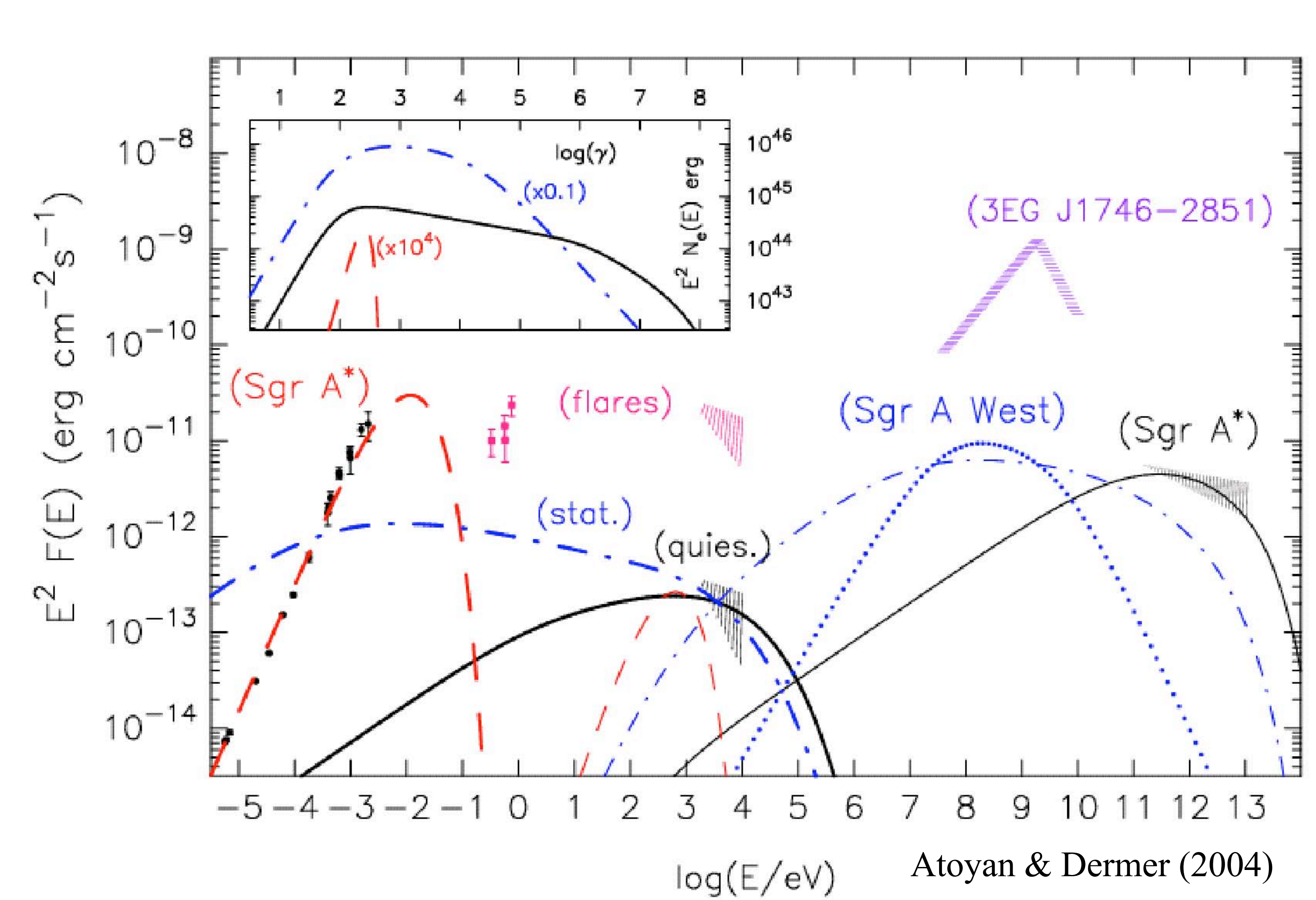
- Flares from instabilities in accretion flow that form shocks at few R_{Sh}
  Fermi (*shock*) acceleration injects electrons with $\gamma \sim 10^6$, -2.2 injection index
- Explains X-ray/NIR flares and short variability timescales
  (cooling and expansion at R~ 20-30 R_{sh} for NIR)

$$t_{cool} \sim 1.4\times10^3 \,(B/10\,G)^{-2}\,(10^6/\gamma)\,s$$

Self-absorbed flares at < 100 GHz from same electrons in "expanding source" scenario (*electrons in the outflow/wind*) on larger distance/time scales

Galactic Center Black Hole Emission:

Sgr A* ADAF + Black-Hole Plerion + Sgr A West, a BH '*remnant*'



Atoyan & Dermer (2004)

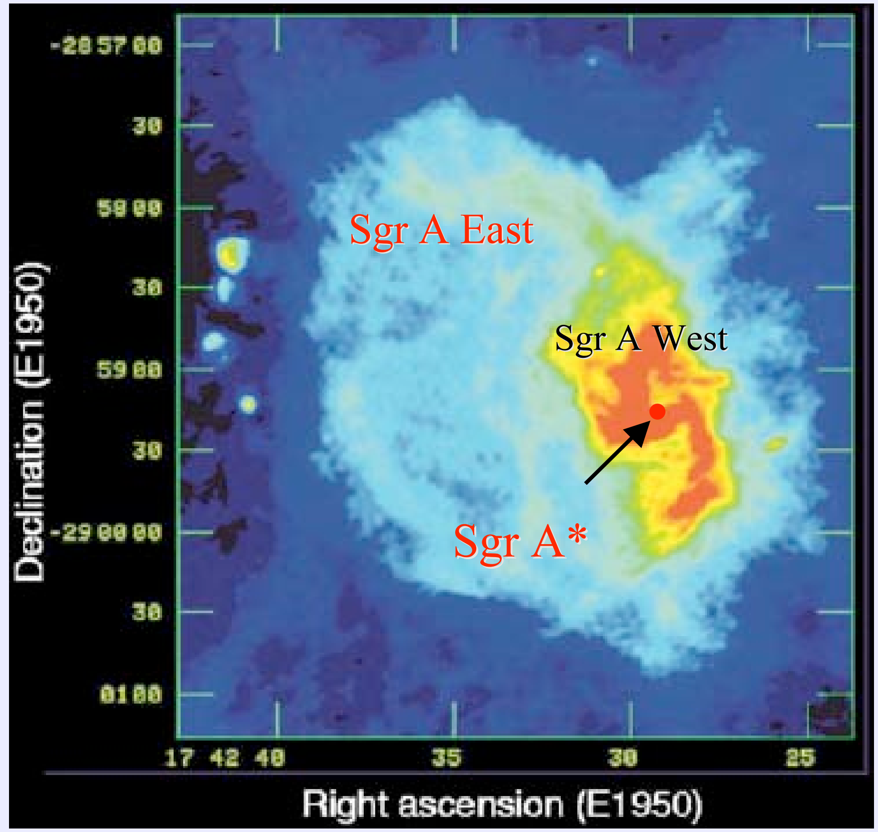
Predict: GLAST detection of quasi-stationary Compton and bremsstrahlung fluxes from pc-scale plerion; no TeV flares (!)

Propagation of GeV electrons powers Sgr A West; *EGRET flux* -- from a young pulsar

Summary

1. Observations imply two emission regions:
   - (i) Inner ADAF region near black hole
   - (ii) Black hole plerion at the termination shock of wind/convective outflow of ADAF
2. X-ray flares are synchrotron emission within ~10 r_S of GCBH
3. TeV γ rays made by black-hole powered plerion, first of a new class of nonthermal emitters
4. Quasi-stationary TeV emission (*southern hemisphere "Crab"*): TeV calibration source;

   Energy-dependent source size;
5. Downstream at larger scales gamma-rays of GeV energies are produced that will be observed by GLAST
6. Synchrotron radio flux from cooled electrons will produce polarized emission that would show up at higher radio/FIR frequencies



6 cm VLA radio of Sgr A East and Sgr A West
(Yusef-Zadeh, Melia, & Wandle 2000)